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Review

Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review

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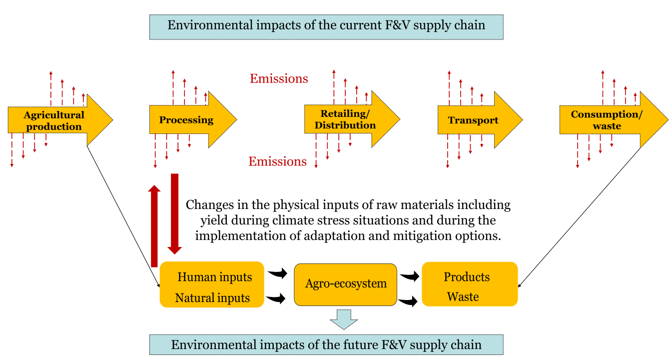
HIGHLIGHTS

- Critical elements affecting environmental impacts of F&V products are discussed.
- Climatic stresses on F&V supply chain are discussed.
- Potential adaptation and mitigation measures in the F&V supply chain are discussed.
- Proposed approach for evaluating environmental costs of the current and future agro-management scenarios

GRAPHICAL ABSTRACT



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ABSTRACT

This study discusses importance of assessing environmental sustainability of fruits and vegetable (F&V) production sector in future climate change (CC) scenarios. For the current production scenario, life cycle environmental footprints of F&V supply chain are discussed considering the influences of: agro-climates, production systems, raw material inputs, post-harvest managements to the products' yield and quality. Potential risks of CC to the sector are discussed in the context of elevated global temperature and carbon dioxide level, ozone depletion and changes in precipitation patterns. Potential risks due to CC are on the productivity and the quality of F&V products, such as texture, color, maturity and nutrients. Increased risk of failure of the current crop protection strategies, e.g. due to pest infestations and different crop-water and nutrient stresses are among the short and long-term risks. It also discusses potential adaptation and mitigation measures to CC, and therefrom argues on the related environmental consequences in the supply chain. From the LCA studies, it was revealed that environmental impacts of F&V supply chain varied as per agro-ecological characteristics and farming systems, e.g. greenhouse vs open-field, organic vs conventional, and grown in different agro-climatic conditions. The nexus among the climatic stresses, potential adaptation and mitigation measures, hence were in the form of potential changes in the raw material inputs and resource flows depending on the preferred future agro-management strategies and farming practices. Adaptation and other management options, included are, changes in: crop calendar, nutrient and pest management strategies, post-harvest handling and improved preservation of F&V products. These are argued eventually being determining factors leading to different environmental footprints compared to the existing management scenarios. Prospective life cycle environmental evaluation of F&V supply chain considering the relationship among product yield and qualities, CC stresses and potential adaptation and mitigation measures is thus a new thrust and direction.

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Contents

1. Introduction

Fruits and vegetables (F&V) play an essential role in nutritious diets (Acharya et al., 2014). In the last two decades, on a per capita basis, global vegetable production has increased by about 60% compared to the preceding decade (1991–2000). Fruit production has also continuously increased because of the growing demand (Huang. S.U., 2004). The rising demand for fresh F&V products is attributed to the consumers' preferences motivated by health issues. For example, "The Food Guide Pyramid," the diagram of nutritional recommendations developed by the U.S. Department of Agriculture and Health and Human Services has advised consuming five to nine servings of fruit and vegetables per day. A "servings of fruit" is defined with respect to the calorie needed. It depends on numerous factors, such as the food group, shape and nutrients provided (further defined in Section 3.1). These recommendations, along with other campaigns, have contributed to educating consumers on the health benefits of F&V consumption (USDA, 2015, 2005).

Major environmental challenges that humans are facing are primarily due to climate change and the predicted future shortage of fossil fuels, e.g. in the agriculture sector (FAO, 2012). Climate change is one of the most prominent global environmental problems, and evaluation of its impact on many production sectors, including agriculture, is relevant (Huang. S.U., 2004). The Intergovernmental Panel on Climate Change (IPCC) has predicted improved conditions for food production over the next few decades in the mid to high latitude areas, e.g. in the northern USA, Canada, northern Europe and Russia. On the contrary, parts of the subtropics, such as the Mediterranean region and parts of Australia, and the low latitudes could experience declining productivity (IPCC, 2007). Agriculture contributes 30–40% of all anthropogenic greenhouse gas (GHG) emissions. Therefore, it is both a significant contributor to climate change while simultaneously being affected by it (Thornton and Lipper, 2014). The various agro-environmental and climatic factors which have the largest impacts in agriculture are changes in the precipitation patterns, such as increasingly frequent droughts, floods, and forest fires, primarily caused due to increasing global temperature and changes in the hydrologic cycle (Huang S.U., 2004). Increasing dependency on raw materials, particularly those derived from the petroleum industry, and the competition for such resources among the different production sectors are also exacerbating the agricultural system vulnerability (Godfray et al., 2010). Hence, relieving environmental pressures during the production of different agricultural products is crucial for all producer countries. Furthermore, the practice of sustainability should be seen not as a requirement to maintain a static situation, but as a challenge to increase the resiliency and adaptability of the natural systems that form the basis of social and economic development (Beccali et al., 2009). It is thus relevant to identify a set of feasible intervention measures, such as, technological innovations and improved farm management practices (Poore and Nemecek, 2018) that can enable the environment to maintain consumer demand (Beccali et al., 2009).

Among the most alarming environmental situations the food production system is facing, is the simultaneous increase in water demand and depletion of water sources (Atallah et al., 2014; Scanlon et al., 2012; Weare, 2009). The stress due to water scarcity has many potential environmental consequences, including the loss of biodiversity (Chapman, 2006). The alternative sources of water and their potential environmental evaluation in the existing F&V supply chain is thus relevant. Secondary effects of climate change to the agricultural system include increased pest and disease pressure, time of appearance, of insects and weeds, migration to new places and over-wintering capacity (Prasad and Chakravorty, 2015). Likewise, frequent exposure of fruits to high temperature can deteriorate the quality, e.g. sunburn, loss of texture and nutritional values (Bindi et al., 2001). Hence, the effects of climatic variations are predicted to worsen the sustainability of F&V production systems, until and unless appropriate adaptation and mitigation measures are implemented. Both adaptation and mitigation measures are necessary to increase the resilience capacity of an agricultural system. Vegetation shifts and alternations on the crop calendar (Teixeira et al., 2018), optimization of resource use efficiency, and management of

logistic facilities to address the impact of seasonal production through improved refrigerated storage and transportation facilities are among the potential adaptation and mitigation measures applicable in the F&V product supply chains (Huang. S.U., 2004). But these will occur with some environmental costs, which are yet to be evaluated.

The Life Cycle Assessment (LCA) method (Rebitzer et al., 2004) is a well-established method to evaluate and compare environmental impacts of alternative production systems for the sustainable provision of goods and services (ISO 14040, 2006). LCA has been limited to evaluating current production systems and practices; hence evaluating future production scenarios is a new thrust/direction/application. The scope of the current study is to present environmental sustainability characteristics of current F&V supply chains, and discuss prospective evaluations considering the impact of CC in the supply chain. With this scope, it (i) overviews general features of the LCA studies of the current F&V production systems, (ii) outlines the potential impacts of climate change, e.g. on crop physiology and yields, (iii) evaluates the adaptation and mitigation measures that could increase the resiliencies of the F&V sector, and (iv) discusses the importance of prospective environmental footprints evaluation of the future production scenarios. The structure of the study is divided in seven sections. Section 2 discusses the employed materials and methods, primarily the approach considered for the management of literature and defining the supply chain with respect to the objectives set for the study. In section 3, environmental footprints of different F&V products are discussed, thereby also highlights the significance of understanding the nexus of resource flows and environmental impact indicators for evaluating future production systems. In Sections 4 and 5, effects of climate change to both on-farm and off-farm stages of the F&V supply chains are presented, and discuss the potential adaptation and mitigation measures. Section 6 discusses the rationale of evaluating environmental trade-offs of different pre- and post-harvest management options, primarily coping the detrimental impacts of CC. Lastly, Section 7 summarizes the current study covering all the dimensions, such as impact, mitigation/adaptation options, and their environmental values.

2. Materials and methods

2.1. Management of literature and methodology

The current study has reviewed 176 publications, comprising studies related to LCA of food supply chains (62 studies, explicitly used in the discussions), climatic impact on F&V crops, adaptations and mitigation options (52 studies), nutritional aspects (15 studies, on nutritional values), and the rest (47) covering these trans-desciplinary fields. Relevant studies were explored by using platforms such as: ISI Web of Knowledge, Web of Science, Science Direct and ResearchGate. Screening of the published literature was guided mainly by the scope set for the current study. Apart from peer-reviewed scientific publications, the search also included periodic reports relevant to the study. Initial screening of the literature was made through the titles, abstract and summary. The bibliographies of the selected publications were also considered for additional references.

The study uses a mixed research method, synthesing both qualitative and quantitative information. The methodological framework designed for the review is shown in Fig. 1. The scope of the study, as discussed above, is illustrated as “Input (A)” (in Fig. 1) led to make choices on the related literature. The parameters considered for the review are shown as “Input B”, in Fig. 1.

2.1.1. Studies related to life cycle assessment of F&V products

LCA is widely used for evaluating environmental performance of different production systems and processes, including of agricultural sectors, e.g. as discussed in Cerutti et al. (2010) and Stoessel et al. (2012) (see detail, in Table 1). It provides a detailed account of material flows, primarily entering to a production system and the products leaving from the system to consumers. The method allows for a complete evaluation of the relationship between the material inputs and outputs of a production system, e.g. from “cradle to grave”, covering the stage of resources/material extraction, processing, consumption and disposal (ISO 14040, 2006). LCA is also used to support decision making processes for prioritizing a product system (Wenzel, 1998).

In the current study, selection of LCA studies was to illustrate (i) system boundary aspects and to discuss the issues for selecting a functional unit of the assessment, (ii) contribution of the different material inputs to the environmental performance of the different stages of F&V supply chains, (iii) the impact assessment results of the different F&V product markets, e.g. fresh and processed products (and their nutritional values), and local or imported products, (iv) relation of different farming practices, e.g. open field and greenhouse, to the environmental life cycle impacts and (v) management strategies that can improve environmental performance of the products in the future.

2.1.2. Studies related to climatic effects on F&V supply chains

Emphases were given to the studies that highlighted the effects of different climatic variables, e.g. temperature, precipitation, and CO_2 level on the production system (Finnan et al., 2002) and on the quality of F&V products (Bisbis et al., 2018). Potential impacts on plant growth and response to pathogens, e.g. due to air pollutants (SO_2, O_3, acid rain etc.) (Prasad and Chakravorty, 2015), were also taken into consideration, and these are briefly discussed in Section 5.

2.2. Supply chains of F&V products

Fig. 2 shows a generic supply chain decision framework that can be used to illustrate whether a product is to be targeted for a processed or fresh market (Tamasese, 2009). The schematic diagram of supply chain covering both fresh and processed products are shown in Fig. 3, but it should be noted that, in general, the two distinct markets have different on-farm raw material inputs, e.g., the farm agro-chemical inputs at the farm level (USDA, 2017). In the current study, a decision-framework was considered to define the product market based on the capacity of storage, harvested quality of the product and the demand in the respective market segments (Fig. 2). These are among the major food quality parameters which were reported to be significantly affected due to detrimental effects of climate change (Section 5). Such decision framework are important whenever the total production volumes of a region/country are to be disaggregated to evaluate for their respective supply chain models.

Generally, raw F&V products are processed as early as possible (between 4 and 48 h, after harvest) to prevent spoilage. The post-harvest process begins with washing and sorting the defective materials. The sorted-out products are often classified as second-choice and used for different purposes, or eliminated depending on specific qualities such as ripening stage, texture and the product grade (Grandison, 2006).

In general, processed market is guided by the type of processed product e.g. for potatoes it is either canned, frozen or dehydrated (Albrecht et al., 2013; Ganesh, 2013; Rothan et al., 1997) (Fig. 3). Likewise, processed tomatoes are often supplied in the form of paste or diced products (Hartz et al., 2008). Fresh products are marketed in a variety of container and grade specifications, e.g. potatoes are usually packed in three general size categories: consumer packs, count cartons, and institutional packs (Belyea et al., 2012). Consideration of packaging materials is important as the environmental cost of producing and managing the different packaging materials is substantial (discussed in Section 3.4). Furthermore, the context of discussing fresh and processed products is also to highlight their different environmental profiles and nutritional values (see Sections 3.1–3.4). A significant differences in the environmental footprints were reported for various types of processed-orange products (Beccali et al., 2009; Coltro et al., 2009; Knudsen et al., 2011) and for tomato products (Del Borghi et al., 2014). Such analyses are important whenever the quantified detrimental effects

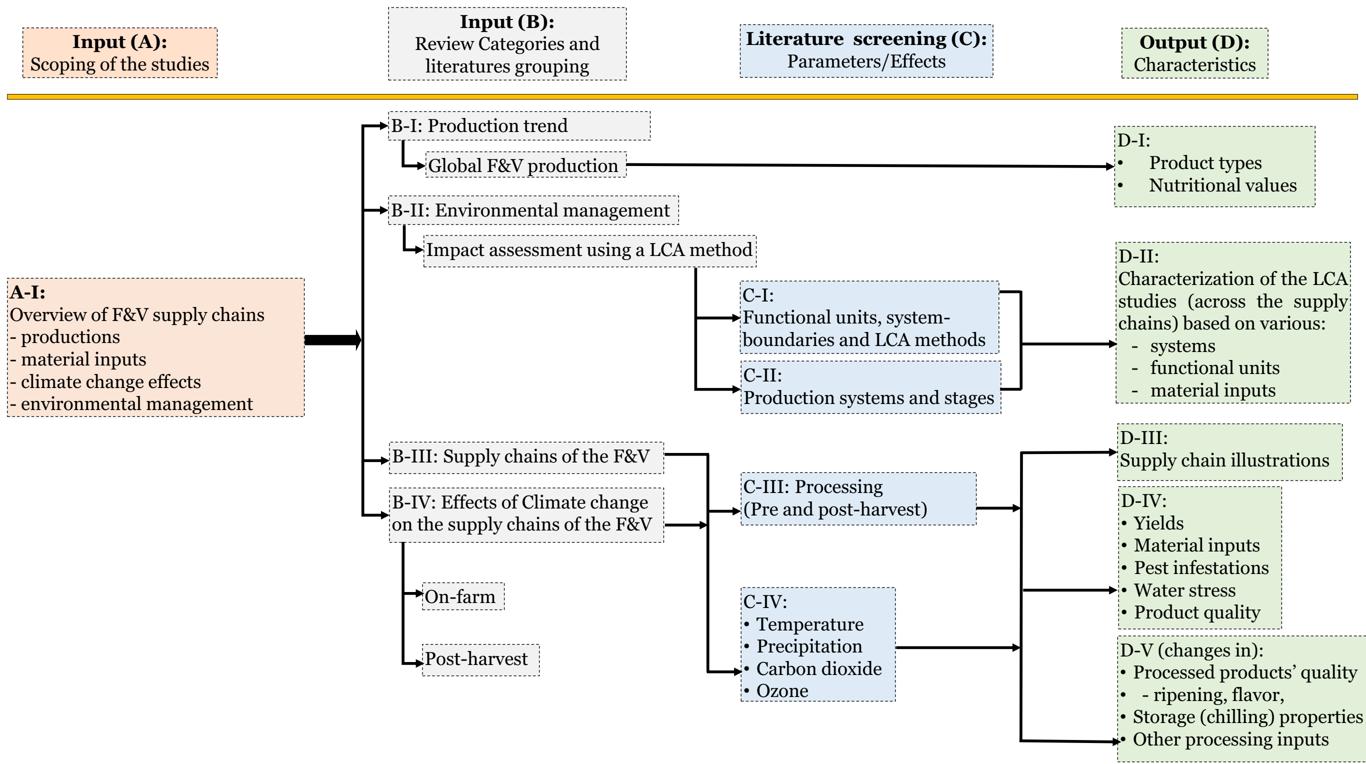

Fig. 1. Framework and approach considered for categorizing the selected literature.

of climate change to the yield and quality are to be considered for devising the future post-harvest management strategies, such as, enhancing preservation of F&V products, including the potential increase in the market shares of the processed products (discussed in Sections 5–6).

3. General characterization of the LCA studies on F&V products

3.1. System boundary and Functional unit

Table 1 shows the characteristics of the LCA studies selected for the review. The system boundary definition and scope definition are vital to ensure comparability of the results obtained for environmental footprints of different production system or processes (Finnveden, 1999; Li et al., 2014). In absence of bounded life cycle, the related processes of a production system are many-fold, even for a simple process/system, which leads to enormous data needs which are difficult to collect (Raynolds et al., 2000). Setting the boundaries with a high degree of completeness is also difficult (Finnveden et al., 2009). Moreover, since boundaries are the way to define the system selected for the life cycle inventory analysis, it is important to include processes involved for producing and supplying the raw materials entering to a product system, major and intermediate feedstocks, and to estimate the resulting emissions. Boundaries can be set to define the spatial, temporal and production chain limits (start and end points) (Li et al., 2014). Moreover, according to ISO standards, a system boundary is determined by an iterative process in which an initial system boundary is chosen, and then further modifications are made by including new unit processes that are shown to be significant by sensitivity analysis. However, considering the scope of assessing a product life cycle, different LCA practitioners may select different system boundaries based on their own experience, which might result in some important processes being overlooked (Li et al., 2014). Nevertheless, given the relevance of this issue on both, assessments of alternative production systems and the food supply in general, it is still useful to consider a broader view of the existing production inventory of the relevant supply chain. In general, there are three major distinctions of system boundaries in life cycle inventory analysis (Guinée, 2002), which are:

(i) between the technical system and the environment
(ii) between significant and insignificant processes, and
(iii) between the technological system under study and other technological systems.

In the selected 62 LCA studies (Table 1), the system boundaries are: cradle-to-market' (14), "cradle-to-farm-gate" (18), 'cradle-to-grave' (6). The remaining studies were defined as 'cradle-to-port' or 'cradle-to-factory gate' or "cradle-to-consumer". In the 'cradle-to-gate' category, the environmental impacts are calculated for the production phase, including all upstream impacts up to the farm gate. The 'cradle-to-market' category includes the evaluations covering the stages: raw material extraction, product's production and distribution at a market gate (Guinée, 2002).

Furthermore, most of the production systems can produce different product(s) that perform one or more functions or provide one or more services and fulfill one or more customer requirements. Generally, issues of multiple products are handled by LCA approaches: subdividing the multi-funtional processes, system expansion and allocation (ISO14049: 2000, 2000). Hence, a functional unit (FU) is required to define a reference unit to quantify the performance and quality of the product system. In a Life Cycle Inventory (LCI) analysis of F&V products, the production function can be considered in terms of quality aspects either from a commercial standard (Martínez-Blanco et al., 2011b; Perrin et al., 2014; Romero-gámez et al., 2012) or a nutritional aspect (Martínez-Blanco et al., 2011a). Almost all LCA studies on F&V products have considered the mass of fresh or dry product as the FU (Table 1), and some expressed as per hectare (ha) (Table 1) (Vinyes et al., 2017; Yan et al., 2016). Despite mass being widely used as FU, its appropriateness is debated (Schau and Fet, 2008), particularly considering the differing quality and nutritional aspects of the products. This is relevant in the widely discussed issues of climate change impact to food qualities (Section 4.2).

A study reported by Worthington (2001) details various nutritional aspects of different products that could be considered for deciding the

Table 1
Characteristics of the selected LCA studies considered for the review. Literature arranged in an alphabetical order.

References	Geography	Selected issues and scope[1]	Characteristics of the study			
			System boundary	Functional units	LCA approach	Product(s)
(Abeliotis et al., 2013)	Greece	a	Cradle-to-farm gate	1 kg product and 1 ha	System expansion	Beans
(Albrecht et al., 2013)	Europe	b	Cradle-to-grave	5 kg of packed products	System expansion	Transport packaging options
(Andersson, 2000)	Sweden	c	Cradle-to-consumer	1 ton product	Allocation	Tomato ketchup
(Anton et al., 2005)	Netherlands	c	Cradle-to-farm gate	1 ton product	Allocation	Tomato
(Atallah et al., 2014)	USA	d	integrated production–transportation planning	1000 boxes	Allocation	Broccoli
(Bacenetti et al., 2015)	Italy	c;h	Cradle-factory gate	1 kg product	System expansion	Tomato purée
(Bartzas et al., 2015)	Italy and Spain	a;e	Cradle-to-farm gate	1 kg product (s)	ND*; Cut-off approach for waste	Lettuce and barley, rotation crops
(Beccali et al., 2009)	European Union	a;d	Cradle-to-grave	1 kg product(s)	Allocation	Citrus products
(Blanke and Burdick, 2005)	Germany and New Zealand	d	Cradle-to-consumer	1 kg product	ND*	Apples
(Bojacá et al., 2014)	Colombia	a	Cradle-to-farm gate	1 ton product	Allocation	Tomato
(Boulard et al., 2011)	France	a;e	Cradle-to-farm gate	1 kg product	Allocation	Tomato
(Carlsson, 1997)	Sweden	a	Cradle-to-grave	1 kg product(s)	ND	Carrot and Tomato
(Cellura et al., 2012)	Italy	f	Cradle-to-grave	1 ton packed products	Allocation	Peppers, melons, tomatoes, cherry tomatoes, and zucchini
(Cerutti et al., 2014)	Global	a	Different boundaries	Review article		Fruits sector
(Coltro et al., 2009)	Brazil	g	Cradle-to-farm gate	1 ton product	ND*	Orange
(de Backer et al., 2009)	Belgium	a	Cradle-to-farm gate	1 kg product and 1 ha	Allocation	Leek
(De Figueirêdo et al., 2014)	Brazil	a	Cradle-to-European port	1 kg product	Allocation	Melons
(Del Borghi et al., 2014)	Italy	c;h	Cradle-to-factory gate	A declared unit = 1 kg of packaged product	Allocation	Tomato products: chopped, peeled and purée
(Edwards-Jones et al., 2008)	Multiple	c;g	Different system boundaries	Review article		Food chain
(Girgenti et al., 2014)	Italy	a;f	Cradle-to-grave	250 g packed product	System expansion	Strawberry
(Ingrao et al., 2015)	Italy	a;c	Cradle-to-farm gate	1 ha	Allocation	Sicilian peach
(Ingwersen, 2012)	Costa Rica	e;g	Cradle-to-market in USA (imported)	1 USDA serving of fruit.	Allocation	Pineapple
(Jones, 2002)	UK	d	Cradle-to-consumer	1 kg product	Means/End analysis	Apple
(Juraske et al., 2009)	Switzerland and USA	g	Farm-to-consumer	DALY**	ND*	51 food commodities and average diets
(Khoshnevisan et al., 2014)	Iran	a	Cradle-to-farm gate	1 kg product(s) and 1 ha	ND*	Cucumber, tomato
(Knudsen et al., 2011)	Brazil	c;f	Cradle-to-market	1 l of juice	System expansion	Orange
(Liu et al., 2010)	China	c	Cradle-to-market	1 ton product	System expansion	Pear
(Giudice et al., 2013)	Italy	c	Cradle-to-market	1 ton product	Allocation	Citrus
(Martínez-Blanco et al., 2009)	Mediterranean area	c;e	Cradle-to-farm gate	1 ton product	System expansion	Tomato
(Martínez-Blanco et al., 2011a)	Spain	e;l;g	Cradle-to-farm gate	5 FUs (mass based, and nutrition contents)	System expansion	Fruits and vegetables
(Michalský and Hooda, 2015)	UK and imports	d	Cradle-to-port	1 kg product	ND*	Apples, cherries, strawberries, garlic and peas
(Milà i Canals et al., 2006)	New Zealand	a	Cradle-to-farm gate	1 ton grade 1 and 2 apple	Allocation	Apple
(Milà i Canals et al., 2007)	UK, New Zealand	e;d;g	Cradle- to-market	1 kg product	ND*	Apple
(Milà i Canals et al., 2008)	UK and Spain	e	Cradle-to-grave	1 kg product on plate	Allocation	Vegetables (Broccoli, salads crops, green beans)
(Milà i Canals et al., 2010)	UK and Spain	e	Cradle-to-grave	1 kg broccoli on plate	Allocation	Broccoli
(Mordini et al., 2009)	Multi-countries, as per the product	g	Cradle-market	kg product (s)	Review article	Oranges and strawberries
(Mouron et al., 2006)	Switzerland	c	Cradle-to-farm gate	1 ha and 'total receipts" in $	Allocation	Apples
(Mouron et al., 2012)	European countries	c	Cradle-to-farm gate	1 ha and 'total receipts" in $	Allocation	Apples
(Muñoz et al., 2008)	Spain	a;g	Cradle-to-farm gate	1 kg product	ND*	Tomato
(Nikkhah et al., 2017)	Iran	a;c		1 ton product	ND*	Peach
(Payen et al., 2015)	Morocco, France	a;c	Cradle-to-market	1 kg product	Allocation	Tomato
(Peano et al., 2015)	Italy	e	Cradle-to-market	250 g punnet strawberries; 125 g	Allocation	Strawberries and berry

(continued on next page)

Table 1 (*continued*)

References	Geography	Selected issues and scope[1]	Characteristics of the study			
			System boundary	Functional units	LCA approach	Product(s)
				punnet of raspberries; 125 g punnet of blueberries		fruits
(Perrin et al., 2014)	Global	e	Cradle-to-farm gate	1 kg fresh yield	Review article	Vegetables
(Perrin et al., 2017)	Africa	e	Cradle-to-farm gate	1 kg product	ND*	Tomato
(Romero-gámez et al., 2012)	Spain	e	Cradle-to-farm gate	1 ha	Allocation	Green bean
(Sanjuan et al., 2005)	Spain	h	Cradle-to-farm gate	1 kg product (as a case study)	ND*	Food processing
(Sim et al., 2007)	UK-imports	d;g	Cradle-to-market	1 ton of grade 1 product (s)	Allocation	UK-fresh produce supply chains
(Soode et al., 2015)	Germany	a;f	Cradle-to-grave	1 kg product packed	System expansion	Strawberries, asparagus and ornamental plants
(Stoessel et al., 2012)	29 countries	e;c;h	Cradle-to-market	1 kg product on plate	ND*	Fruits and vegetables (34 types)
(Tecco et al., 2016)	Italy	a	Cradle-to-market	1 kg product	ND*	Raspberry
(Torrellas et al., 2012)	Spain, Hungary, Netherlands	f	Cradle-to-farm gate	1 ton product	Allocation and System expansion	Tomato and ornamental plant
(van Evert et al., 2013)	Global scale	e	Cradle-to-farm gate	1 ton product	Allocation (bio-physical tool)	Potato
(Vinyes et al., 2017)	Spain	c;e	Cradle-to-grave	1 kg products	Allocation	Apple and peach
(Weber and Matthews, 2008)	USA	g	Input-Output LCA	A household-year	Input-output LCA	F&V consumed in US households
(Williams et al., 2013)	UK and others	d	Cradle-to-market	1 kg product	Allocation	Potatoes
(Yan et al., 2016)	China	a;e	Cradle-to-market	1 hectare (ha) and kg product	Allocation	Orange, pear, apple, banana, peach

[1]Review Criteria and scopes for the LCA studies.
a = production systems (stages of supply chain, protected/unprotected farms, and open-field systems); b = packaging and logistics; c = contributions of raw material inputs; d = local vs imports; e = agro-environmental factors; f = LCA approaches; g = functional units (FU) and nutrients as FU; h = processing of food and energy accounting.
*ND = not defined clearly. However, it is expected that most of the studies followed the attributional LCA approach.
**DALY = disability adjusted life years.

FU. Ingwersen (2012) suggests "one USDA serving of fruits" as an appropriate FU when different products are to be compared, or when the life cycle impacts of a product are to be enumerated for environmental labelling. This is also relevant because a single fruit might provide more than one 'serving', along with other nutritional benefits. The recommended number of fruit and vegetable servings per day per person can be calculated according to the USDA definitions of serving sizes (Patterson et al., 1990; USDA, 2010, 2005). "The 2015–2020 Dietary Guidelines for Americans" (USDA, 2010) suggested that person's needing 2000 cal per day requires 2 cups of fruit and 2.5 cups of vegetables in their daily diets, however the average American adult consumes only 1.1 cups of fruit and 1.6 cups of vegetables per day (Stewart et al., 2016). For fruits, a serving was defined as "an average piece of whole fruit or six ounces of fruit juice". Likewise, for vegetables, one-half cup, cooked or raw was defined as a serving unit (Patterson et al., 1990). It is "…a normalized unit of food intake for a diet that is composed of a recommended number of servings of foods from food groups (e.g. fruits, vegetables, proteins, grains)" (Ingwersen, 2012). For example, as per the USDA definition, "1 cup of fresh fruit" of raw pineapple or orange are 165 g and 180 g respectively; for chopped vegetables, one cup of raw broccoli is 90.93 g (USDA, 2015).

Studies such as Ellingsen and Aanondsen (2006), Saarinen et al. (2012) and Ziegler et al. (2003) have used a FU-'similar-portion size', but that was not normalized against a recommended diet.

Consumers typically do not purchase foods based on mass content, and additionally mass varies along with water content (Ingwersen, 2012). Hence, if the environmental evaluation of F&V products are to be made on a nutritional basis, it is important to consider their nutritional qualities at different stages of handing the product. The results suggested by Yan et al. (2016) showed that environmental impacts evaluated per 1 ha, gram of Vitamin C and economic benefits can bring to different conclusions on the environmental profiling of fruits (further discussed in Section 3.4.5).

Furthermore, there are many studies which have explicitly reported the losses of different food nutrients due to the different climatic variations (Ayyogari et al., 2014) (see section 4), and in the future, to minimize losses, more food items may require refrigerated transport and storage, which demands additional resources. Hence, whenever sustainability assessments of F&V products are to be linked with the daily human dietary requirements, selection of appropriate reference flows and FU that reflect the product quality and performance is relevant. This is one of the research gaps in the LCA studies.

3.2. Stages of F&V supply chain and LCA modelling

Depending on the crops, detailed LCI modelling of fruit production systems can be facilitated by splitting the whole system into six stages: (i) the nursery phase for producing rootstocks or cuttings and whips ready to plant, (ii) planting and field preparation for the orchard, (iii) the early low production phase articulated with system's immaturity, (iv) full production phase, (v) the low production phase characterized due to plant senescence, and (vi) the removal and disposal of plants (Cerutti et al., 2010; Milà i Canals et al., 2006). Stages (iii-iv) are the main domains where the production activities are characterized with different levels of material inputs and with different volume of the delivered outputs. The outputs (product and emissions) are variable over the life cycle years of a production system. Likewise, despite the other stages are not providing output for the market, they still contribute substantially to the overall environmental footprint.

Compared to the vegetable supply chain and annual crops, the fruit-tree life cycle constitutes variable durations (10–30 years) which can be considered similar to perennial crops cultivated on arable land. For example, in orange, the production of fruits involves nursery/orchard development as a sub-system, hence, the LCI should include (i) production of seedlings/plantings and (ii) production of the main crops. In general, the main crop production system includes tillage, planting, application of agrochemicals, irrigation and harvest. In the fruit-trees, the harvesting stage can be followed by field restoration, which is normally at the end of the orchard life cycle (e.g. apple and orange). Hence, in the cases where the system boundary includes orchard management and field restoration processes, related LCI and the associated impacts should also be considered. They are mainly characterized by undesired

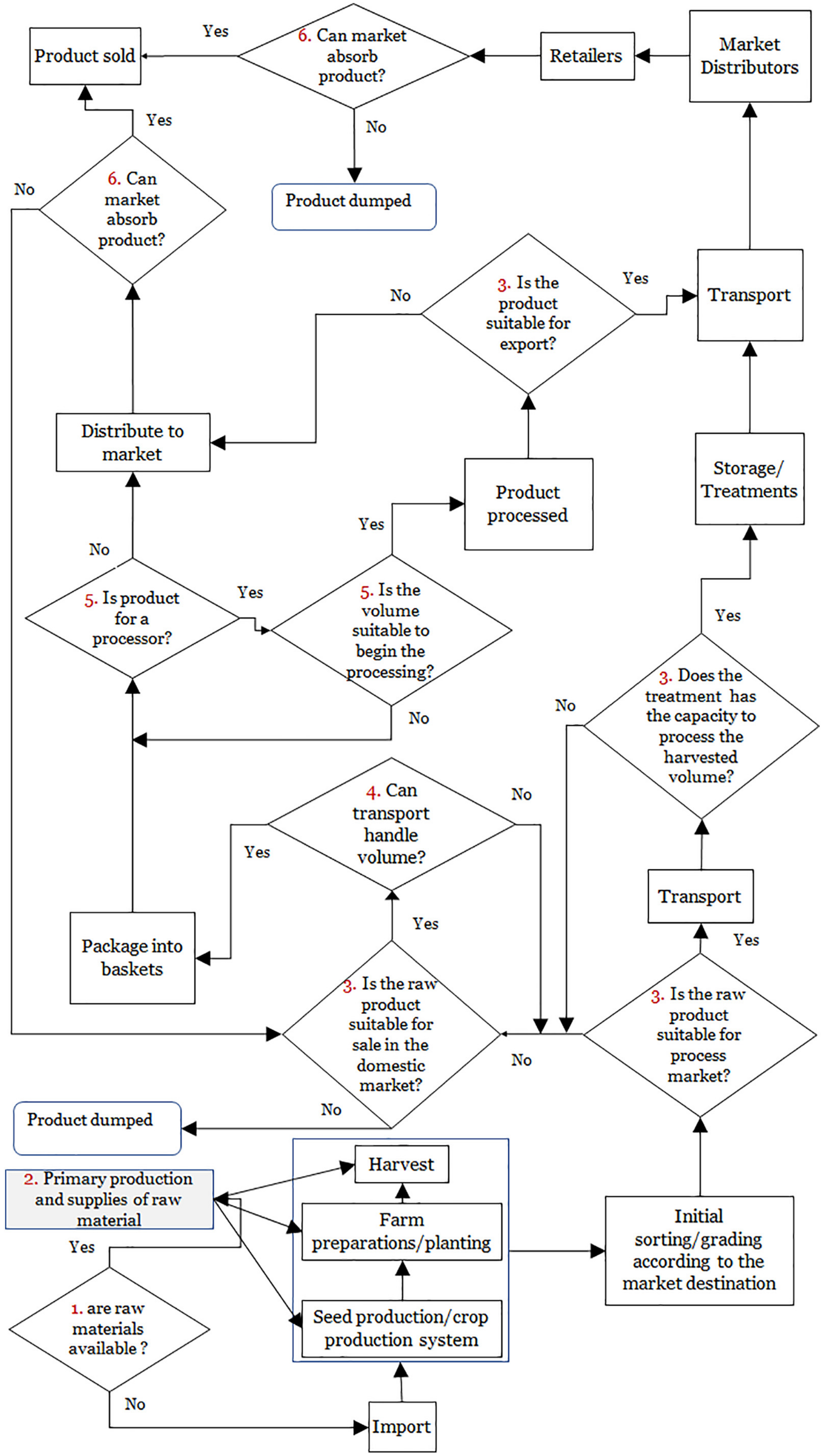

Fig. 2. Generic supply chain networks for F&V products. Network diagram based on (Tamasese, 2009).

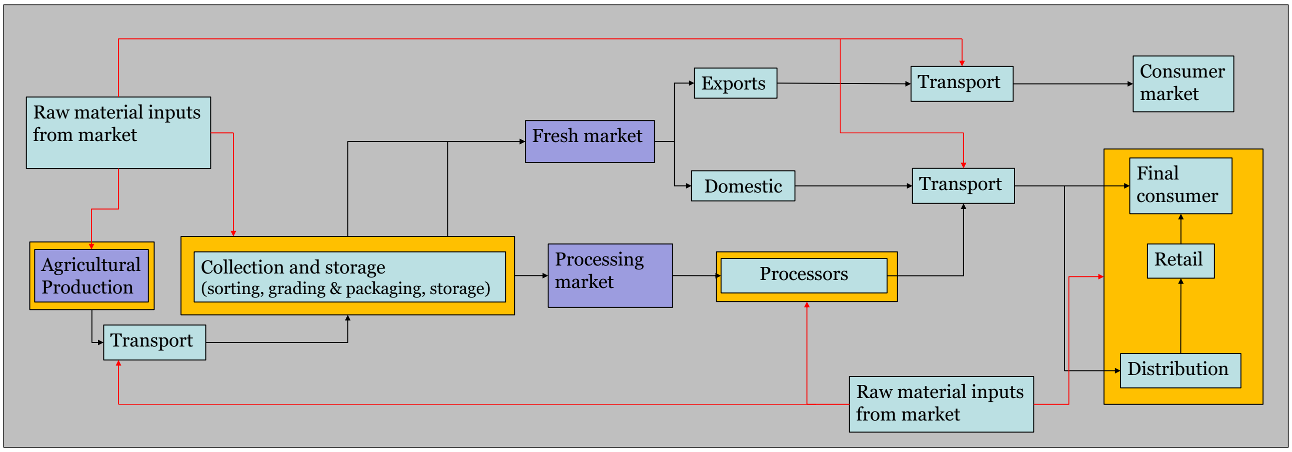

Fig. 3. Schematic supply chain of F&V products.

emissions related to the production of seedlings or cuttings, their transport to the main crop land (Cerutti et al., 2014) and soil organic carbon changes that may occur during the field restoration process, similarly as modelled in other perennial crops (Parajuli et al., 2017).

Another important resource flow in the F&V supply chain is water for the production of crops and for post-harvest processing, as several crops (e.g. carrots, bananas, cucumbers, lettuce, spinach) are cleaned after the harvest. The process of cleaning food commodities consumes substantial volume of water (generally ranging from 0.4–4.4 l of tap water per kg of crop) (Hernández et al., 2000). Likewise, accounting losses is also relevant, as the post harvest losses and waste in the F&V supply chain until at consumers gate was reported to be high as 13–38% (Gustavsson et al., 2011). Furthermore, about 20% of the most of the perishable food commodities are wasted due to lack of suitable refrigerated system and inaccessibility of energy (Defraeye et al., 2015). These losses represent huge amount of resource use, e.g. energy and water, which is about 38% of all energy consumed in the food industry (Gustavsson et al., 2011).

Heller and Keoleian (2003) reported that the continuous supply of diverse selections of foods for U.S. consumers and those in other developed countries relies heavily on processing and packaging to preserve food. These aid in the transportation of fresh foods to areas with limited growing seasons. Preservation is essential to maintaining the product's quality (Garnett, 2006). With regard to resource use, Stoessel et al. (2012) reported that for a standardized container with an average load of 10 ton, the average power consumption for refrigerated transport is 3.6 kWh/TEU (TEU = twenty-foot equivalent unit). Resource use and the impact of refrigerated cooling depends on the types of horticultural crops and their controlled atmosphere storage potential, e.g., temperature and relative humidity. Summaries of storage requirements of different fresh fruits, vegetables, cut flowers, and other horticultural crops is reported in Kenneth et al. (2016). These studies showed that there is a direct relationship between the source of a fresh food product and energy consumption, depending on the need of refrigerated transport and storage facilities.

3.3. Contribution analysis of F&V supply chain

The contributions to the life cycle environmental impacts from the different stages of the F&V supply chain are varied. For example, in a tomato supply chain the carbon footprint related to the cultivation stage ranged from 31 to 58%, and the packaging subsystem contributed in the range of 7 to 54%, depending on the volume of fresh tomatoes (Del Borghi et al., 2014). Environmental impacts related to the cultivation phase are mostly associated with the fertilizers, diesel use and emissions due to land use change.

For tomato produced in a greenhouse system, Payen et al. (2015) reported that nonrenewable energy consumption was mostly related to the transportation process (43%), followed by cultivation (35%), packaging (17%) and 4% of the impact was related to the nursery development stage. The production of greenhouse-fabrication materials and the emissions during the production of tomatoes in the greenhouse jointly contributed 37% of the total carbon footprint (calculated in 100-years perspective), and the remaining processes, such as packaging and transport, contributed 17% and 44% of the impact respectively (Payen et al., 2015). Freshwater eutrophication related to the cultivation stage was 66% of the total impact (0.17 g P per kg tomato), whilst in the case of marine eutrophication the transportation stage contributed the most, 38% of the total impact (0.21 g N per kg tomato). Likewise, for the water footprint, about 94–98% of the impact (i.e. 21–30 l water per kg tomato) was related to the production stage, and the rest was covered by the nursery development and the transport of the product (Anton et al., 2005; Del Borghi et al., 2014; Payen et al., 2015). In a study of tomato-ketchup, the packaging and food processing stages were the main hotspots for most of the impact categories. The primary energy use was related to the storage time the product are to be placed in a refrigerator (household phase) (Andersson et al., 1998). For the different types of tomato products (paste, diced puree etc.), the contribution was fairly constant, as the products had similar processing procedures (Del Borghi et al., 2014). These showed for the same fresh product, as per the production system and types of processed product, impacts would vary.

In the case of apples, the cultivation stage contributed 36–49% of the total GHG emissions (Vinyes et al., 2017; Iriarte et al., 2013). Likewise, about 14% of the non-renewable energy demand, 93% of the acidification potential, 84% of the fresh water eutrophication and 99% of the total water depletion potential were related to the cultivation stage (Vinyes et al., 2017). The rest of the supply chain were also the major contributor, example, of the total GHG emissions, the contribution from the retail was 39%, consumption (28%) and disposal (2–5%) (Vinyes et al., 2017).

In orange production systems, the processing phase was the largest emitting stage in the supply chain (Giudice et al., 2013). Likewise, the contribution due to the transport, particularly for the imported products was paramount. For example, in the case of importing processed orange juice to Denmark from Brazil, about 58% of the total carbon footprint (total impact = 0.42 kg CO_2 eq per liter juice, (in 100-years perspective) was due to the transportation (Knudsen et al., 2011). In their studies, the rest of the impact was related to the other stages, such as processing (17%), cultivation including the farm inputs (26%). Non-renewable energy (NRE) use was mostly related to the processing stage of the orange, and it contributed 54% of the total impact (6.7 MJ eq per liter juice), followed by cultivation, including farm inputs (26%) and transport

(20%). In their studies, the environmental impacts of the product was credited due to the co-production of orange residue pellets, which was assumed to substitute the production of barley, an alternative animal feed, such as offsetting about 11% of the reported acidification potential (AP) (0.003 kg SO2 eq per liter juice). About 85% of AP was related to the transportation stage, followed by the farm production processes (including cultivation) (26%). They also reported that with the use of manure, the decrease in the global warming potential (GWP) for orange at farm gate was about 11% compared to not using it (Knudsen et al., 2011).

Likewise, GHG emissions (100-years perspective) for producing broccoli and fresh tomato were −0.36 and 0.89 kg CO_2eq per kg product respectively. Negative impact was primarily due to the assumption made on the avoided impacts, in their case, it was synthetic fertilizer, as compost was recirculated back to the field as a source of fertilizer (Martínez-Blanco et al., 2011a, 2011b, 2009). Similarly, the utilization of waste streams for the productive uses showed positive contributions which lowered the other impact potentials, e.g. eutrophication and acidification potentials (Martínez-Blanco et al., 2011a, 2011b, 2009). These are the examples how the results of LCA of F&V supply chain can vary depending on the method chosen for the evaluation.

3.4. Factors influencing the results on the environmental impacts

In the reviewed LCA studies, the cropping systems were highly variable in terms of the production regions, farming practices, scale of material inputs and the yield of the specific products. These variations led to different environmental footprints of the assessed products in different regions (Perrin et al., 2014). Environmental impact was also varied based on cropping system characteristics such as: farm inputs (Khoshnevisan et al., 2014), production system (greenhouse versus open-field) (Martínez-Blanco et al., 2011a; Romero-gámez et al., 2012), types of greenhouse (Boulard et al., 2011), and production region, e.g. temperate, Mediterranean, or tropical (Peano et al., 2015; Vinyes et al., 2017; Yan et al., 2016). Fertilizer management, including application rate and the consideration of mineral fertilizer vs. compost (Martínez-Blanco et al., 2011b, 2011a), farm types, e.g. conventional, integrated, or organic (Abeliotis et al., 2013; de Backer et al., 2009), and the LCA approaches, e.g. with or without consideration of the avoided burdens (Bartzas et al., 2015; Pelletier et al., 2015; Torrellas et al., 2012) also varied the results. Results reflecting the influence of different production factors are discussed below.

3.4.1. Material inputs

Often the raw material inputs for agricultural products (fuel fertilizers and pesticides, and energy) are the dominant contributors to the most of the environmental impact (Liu et al., 2010; Pimentel et al., 1973; Nikkhah et al., 2017). For example, production of N-fertilizer and undersired emissions such as, nitrous oxide, ammonia and methane were the major contributors to global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP) (Parajuli et al., 2017, 2016; Del Borghi et al., 2014). Likewise, toxicity was primarily due to the production and use of agro-chemicals (Andersson, 2000; Edwards-Jones et al., 2008).

Mouron et al. (2006) analyzed an input-impact map by illustrating the level of statistically significant correlations of three impact categories (energy use, aquatic ecotoxicity and aquatic eutrophication) with the inputs. The study showed the highest correlation of energy use with diesel consumption and with the inputs connected with background processes, e.g. diesel use in farm equipments and the buildings for machinery shelter. Likewise, N-fertilizer and other plant treatment products also contribute substantially to energy use. In contrast, it was reported that K-fertilizer was neither correlated to energy nor to aquatic ecotoxicity or aquatic eutrophication.

Moreover, another important factor in the N-fertilizer input is nitrogen cycling and losses. Increasing amounts of N-fertilizer applied within a specific cropping system increases the risk of nitrate leaching (Simmelsgaard, 1998). Manipulation of factors such as the ploughing period and choice of rotational crops are among the important measures to impact N-mineralization and seasonal N-uptake, hence minimizing nitrate leaching (Parajuli et al., 2015).

In addition, impacts due to irrigation was also reported to be substantial, due to necessity of pumping large volumes of water and energy used to pump. There are opportunities to reduce GHG emissions by improving the irrigation practices and in the production and operation of agricultural machinery (Ingrao et al., 2015). This is equally important in the changing climatic conditions, and for prioritizing for optimal use of farm implements and irrigation facilities. Nevertheless, the scale of environmental degradation depends on-to what level changes in the raw material inputs will occur to address the consequences of climate change in the food production system (discussed in section 4). Hence, there are potential research avenues for evaluating and analysing the LCI and environmental impacts of the future production systems.

3.4.2. Production systems

Despite, greenhouse-based production system had increase in the yields of different F&V products, it showed mixed results with respect to different environmental impact categories, such as for tomato carbon footprint and fossil fuel consumption was higher than the open-field system, whilst acification potential was the opposite (Bartzas et al., 2015; Payen et al., 2015). For example, environmental impact for producing 1 kg of tomatoes in an open field and under heated greenhouse were reported respectively as GWP (50 and 74 g CO_2 eq), depletion of non-renewable resources (0.48 and 0.36 g Sb eq), AP (0.64 and 0.48 g SO_2 eq), EP (0.15 and 0.12 g PO_4^{-2} eq), energy consumption (1.2 and 0.9 MJ eq), and water consumption (13 and 24 l) (Muñoz et al., 2008). In a greenhouse system, the infrastructure contributed most to the different environmental impact categories. Hence improvement in the life span of materials such as polyethylene cover, use of alternatve materials (e.g. polycarbonate and biodegradable materials) are relevant to mitigate the impacts (Bojacá et al., 2014; Girgenti et al., 2014) now and in the future.

3.4.3. Seasonality and production regions

The important parameters to be considered in comparing foods produced in different countries/regions are seasonality of the production and harvest time. For example, GHG emissions to produce green beans and lettuce in a tropical climate averaged 0.05 kg CO_2 eq per kg fresh yield (Milà i Canals et al., 2008), whilst the same products grown in a cold climate (in a heated greenhouse) averaged 0.45 kg CO_2 eq per kg fresh yield (Anton et al., 2005; Boulard et al., 2011; Martínez-Blanco et al., 2011b; Perrin et al., 2014). Supply of the off-season apples requires additional time for storage; the impact is thus in the additional energy use and in product loss. The variability in % of apple loss ranged from 5 to 40% over 4–10 months storage. It was also argued that losses may increase linearly up to 25% after 10 months storage. Moreover, the need of storage is dependent on the specific product (Milà i Canals et al., 2007). Decisions about crop scheduling, agro-chemical applications and harvest time in future production scenarios (further discussed below) are relevant to optimize yield and with minimal environmental footprints. These areas are yet to be explored in the LCA research domains.

3.4.4. Local vs import

In a discourse of ‘food miles’, Blanke and Burdick (2005) discussed the relative energy-advantages of home grown heated-greenhouse versus field grown imported products. They concluded that less primary energy was required for domestically grown apples, and suggested that it also provides other socio-economic returns to a local society. Jones (2002) compared the environmental impact of either importing or locally producing apples in Britain. They analyzed different means of transporting the product and selling from the different sales point

(e.g. supermarket and home delivery box schemes). The study revealed that local sourcing of apples resulted in 87% less CO_2 emissions than the imported apples purchased at a supermarket. Environmental performance, such as fuel consumption and related air-borne emissions due to the transportation of commodities, is dependent on the transport mode and the distance between the production-processing-consumption sites (Beccali et al., 2009).

The production and transportation cost is also influenced by the localization of supply chain, e.g. as was reported for the broccoli supply chain within the eastern U.S. and across the country (Atallah et al., 2014). It was argued that localization effects are seasonal, particularly for fresh horticultural crops, and are related to the production seasonality in the areas undergoing localization. They further argued, "even with 30 percent expansion in the acreage of broccoli production in eastern U.S., the share of eastern-broccoli production in the eastern markets (i.e. localization) would only reach 6 percent without increasing supply chain costs or consumer prices."

Another important aspect in the environmental evaluation is whether storage of a product would disqualify the need of the long range transportation, particularly if domestically produced products are to be compared with the ones transported from elsewhere. For example, a LCA study on Braeburn apples showed that primary energy use for German apples is nearly 6 MJ per kg of fruit, of which 13% of the total energy used, was for storing the apples at 1 °C during the winter months. By contrast, the overall energy requirements for importing New Zealand apples were higher by 25%, or 7.5 MJ per kg. Seasonality was thus an important factor. In New Zealand, apples are harvested at the end of March and normally transported for 28 days by sea and sold in Germany in April. Whilst in Germany apples are harvested in mid-October and stored for five months before being sold in mid-March (Blanke and Burdick, 2005). The study, however, did not consider waste-apples in storage or during transit. Furthermore, modelling consumer preferences and seasonality of demand is relevant, but it is complex to model in terms of environmental impact assessment.

To reduce the environmental impacts of producing and supplying fresh apples, it was recommended that local sourcing should be promoted. Similarly, domestically produced apples were preferred, especially when there is in-season production in a purchasing country that allows storage for a shorter period of time (less than 4 months) (Milà i Canals et al., 2007; Sim et al., 2007). In the same manner, local sourcing and home-grown production were reported as the most efficient options, followed by national sourcing and then the imported product (Jones, 2002; Kooijman, 1993). Kooijman (1993) reported that energy consumed in the packaging of fresh imported peas was 8.5 MJ/kg peas, whilst the packaging-energy consumption for locally sourced peas was a tenth of the imported peas. Likewise, energy consumption for carrots imported from Italy to Sweden was almost double the Swedish production. However, regardless of the preference for local production, when the production of tomatoes in a heated greenhouse in Sweden was compared to imported product (unprotected production in Spain), the latter system performed better. When comparing among the alternative transportation systems for tomatoes, distributing by plane was 10 times more energy intensive than distributing by road. Such factors should be carefully considered in the environmental modelling of F&V products, particularly if the future system entails with relocation of the production areas, and the logistics become crucial issue.

3.4.5. Nutrition and environmental impacts

Yan et al. (2016) suggested, on a ha basis, the carbon footprint (in 100-years perspective) of: banana ranged was 9.7 t CO_2 eq, and for pear, apple, and orange (8.6, 8.2, and 7.1 t CO_2 eq ha^{-1}, respectively) and lowest for peach (5.9 t CO_2 eq ha − 1). In contrast, based on the nutritional value (gram of Vitamin C), orange had the lower impact (0.5 kg CO_2-eq g^{-1} Vc, whereas the rest of the fruits ranged from 3.0–-5.9 kg CO_2 eq g^{-1} Vc).

Likewise, Gottfridsson (2014) reported that the carbon footprint of fresh and frozen commodities were varied because of different nutrition index. The impact for the frozen turnip was higher than the fresh, since it has lower nutrional index. The same conclusion was for carrot, and interestingly fresh carrot was preferable than turnip (based on GHG emission per nutritional index). Likewise, the carbon footprint per nutrional index of frozen carrots and turnips was lower after cooking compared to than before, whilst the fresh product had comparable impact intensity before and after cooking. They further argued that nutritional index varies depending on pre- and postharvest factors. All these arguments emphasized that both for the current and future environmental evaluation of food crops, nutritional values are relevant to consider, since their main functionality is to provide nutrition for human health, and the nutritional values are different in a way we process and consume them.

4. Climatic stresses on the F&V supply chains

The effects of climatic variations are discussed with respect to the two distinct stages of F&V supply chains: on-farm and off-farm. The former represents all the processes involved during the cultivation until harvest, whilst the latter stage represents the processes involved after the product leaves the farm and reaches the consumers' plate.

4.1. On-farm characteristics

4.1.1. Carbon dioxide

Greenhouse gases such as CO_2 and CH_4, primarily emitted due to anthropogenic actions, are not only responsible for global warming, but also induce effects on the growth and development of plant physiology (Bisbis et al., 2018). For instance, potato plants under an elevated CO_2 level can have higher photosynthesis rates, but as the level rises, eventually the rate will decline (Finnan et al., 2002). Likewise, accelerated fruit ripening is one effect of elevated CO_2 concentrations, which may lead to more spoilage, resulting to higher intensity of environmental footprints. The results on the impact of climate change on the crop yield explain the complex regional patterns for: the projected climate variables, CO_2 effects, and their impacts on the agricultural systems (Parry et al., 2004). It is expected that increase on atmospheric carbon dioxide (CO_2) concentration may increase the agricultural biomass growth, e.g., in tubers and depending on the crops. Meanwehile, it was also suggested that the magnitude of CO_2 fertilization effect is dependent on the availability of mineral N and the ability of plants to obtain it (Kanter et al., 2016). Hence, the potential future growth in the agricultural biomasses is also argued to take up nitrogen (N) that may otherwise be lost as N_2O (Kanter et al., 2016). However, the variability of yield in response to CO_2 is high, in a similar way as the variability of climate, hence understanding yield interactions with CO_2 is equally important as that of understanding the impact of climate on the yield itself (McGrath and Lobell, 2013). Here, it should be noted that N_2O is one of the major anthropogenic GHG emissions.

4.1.2. Drought and salinity

Drought induced by climate change and other anthropogenic activities can have adverse impacts on horticultural crop production (Snyder, 2017). It has a tendency to induce sprouting of tubers in potatoes (Prasad and Chakravorty, 2015). The consequences are on the reduction of yield as well as on the water content and quality of vegetables, e.g. in spinach (Prasad and Chakravorty, 2015). Drought increases the salinity in the soil, thus affecting the osmotic potential and therefore the loss of water from plant cells leading to reduction in productivity (Myers et al., 2017). Higher salinity can also inhibit physiological and biochemical processes including germination rate and germination percentage (Amira M.S. Abdul Qados and Abdul Qados, 2011), and reduces the rate of photosynthesis and respiration (Hughes, 2007) in plants such as beans, cabbages and potatoes (Baysal et al., 2004; Kaymakanova et al., 2008). Other crops, including cucumber, eggplant, pepper and

tomato, are also regarded moderately sensitive to saline soils (Hughes, 2007).

4.1.3. Air pollutants and UV radiation

Air pollutants such as SO_2, O_3 and acid rain can affect plant tissues and crop response to pathogens (Prasad and Chakravorty, 2015). Increased concentration of air pollutants, such as dioxides of nitrogen and sulfur, not only increase eutrophication and acidification potential (Forsius et al., 2010) but also causes degradation of the ozone layer (Kampa and Castanas, 2008). Vegetables such as tomato, cabbage, potatoes and sugar beets are susceptible to UV radiation (Hughes, 2007). Some of the effects include suppressed photosynthesis, increased susceptibility to viruses, and dry-weight of tomatoes and beans (Benda, 1955; Hao et al., 1997).

4.1.4. Temperature

Crop yields showed a strong correlation with temperature change and duration of heat or cold waves (Hoffmann, 2013). Many scientific studies indicated that extreme weather events are likely to become more frequent or more intense with human-induced GHG emissions (Lenderink and van Meijgaard, 2008). Fluctuations of temperature are also expected due to climate change (R. et al., 2012) indicating that most of the warming reported in the northern hemisphere over the past four decades can be attributed to an increase of mean minimum (mostly nighttime) temperatures. Likewise, studies on extreme meteorological events argued that even a short period of abnormally high temperatures can have a harmful effect on crop growth and yield (Emberson, 2017). Likewise, high temperature stress can adversely affect vegetable production as many physiological, bio-chemical and metabolic activities of plants are temperature dependent. For example, germination of cucumber and melon seeds is largely suppressed at 42–45 °C, and watermelon, squash and pumpkin seeds germinate poorly at 42 °C (Kurtar, 2010). Temperatures above 25 °C affect pollination and fruit-set in tomatoes (Ayyogari et al., 2014).

Photosynthetic activity is proportional to temperature variations. The rate of biochemical reactions catalyzed by different enzymes are increased due to elevated temperature. It is also reported that above a certain temperature threshold, plant tissues may have reduced tolerance to heat stress (Xu et al., 2015). Increased temperature during the growing season results in early maturity (Craufurd and Wheeler, 2009). Potatoes are very sensitive to temperature and day length, mainly for tuber formation and flowering. Tuber formation is optimum at 20 °C. Temperatures above 21 °C can cause a dramatic reduction in potato tuber yield and at 30 °C complete cessation of tuber formation can occur. It was also argued that with a predicted temperature rise between 1 and 1.4 °C, the global potato yield may decrease by 18 to 32% (without adaptation to climate change) and by 9 to 18% (with adaptation) (Hijmans, 2003). For example, the productivity of potatoes may decline in India by about 13% due to regional vulnerability of the agricultural system anticipated based on the effects of the climate change experienced in the country. This productivity loss is more likely if there is 3 °C temperature rise and if proper adaptation measures are not applied (Singh et al., 2013). On the other hand, increased temperature may favor the cultivation of potatoes in the temperate and cold northern European climate and other frost prone areas (Ayyogari et al., 2014). Another consequence of temperature rise on potatoes is browning, which occurs due to conversion of starch into sugar at low temperature. It is prone in the areas where night temperatures drop below the optimal (Ayyogari et al., 2014). Hence, both higher and lower temperature variation compared to the threshold have been reported to have detrimental effects on the quality and yield of potato production, depending on the production regions.

Regarding the plant diseases, increased temperature is also expected to have an adverse impact due to increased pest infestations in several complex ways (Ayyogari et al., 2014) including disease incidence, host-pathogen interactions, time of appearance of the insects and weeds, migration to new places and overwintering capacity (Prasad and Chakravorty, 2015). The impact of climate change also has the potential to modify host and pathogen physiology and resistance. It may also potentially change the stages and the rate of development of pathogens (Houston et al., 2018). Furthermore, temperature, rainfall, humidity, radiation or dew can affect the growth and spread of fungi and bacteria. Other critical factors that can influence plant diseases are air pollution, particularly ozone and UV-B radiation as well as nutrient availability to plants (Boonekamp, 2012). An adaptation measure that was suggested was altering the planting month to facilitate plant growth with optimal temperature (Boonekamp, 2012). Mitigation measures can also be in the form of demanding specific types of agrochemicals that can inhibit the growth of fungi and bacteria in areas which are susceptible. These have environmental implications, and thus need to be quantified.

4.2. Off-farm and nutritional characteristics

Beyond basic nutritive value, F&V are also rich in biologically active components e.g. ascorbic acid, sugars and phenols that impart health benefits. The concentration of many biologically active components can increase with increasing CO_2 level, but there is also a reduction in the protein and mineral content (Ayyogari et al., 2014). Changes in ripening behavior are likely to occur when fruit and vegetable crops are exposed to higher temperatures prior to harvest. As an example, exposure of tomato fruits to temperatures above 30 °C suppresses many of the parameters required for normal fruit ripening, e.g. color development, softening, respiration rate and ethylene production. Apples exposed to direct sunlight had a higher sugar content compared to those grown under more shaded conditions (Buescher, 1979). Frequent exposure of fruits to high temperature (35–40 °C) can result in sunburn and loss of texture (Moretti et al., 2010), e.g. in apples and avocadoes (Woolf et al., 2000). Many studies have reported that quality of fresh F&V crops are directly and indirectly affected by exposure to high temperatures, elevated levels of CO_2 and ozone. Since temperature also has an effect on photosynthesis, the impact can be in terms of different physio-chemical alterations in the F&V products, e.g. in sugars, organic acids, firmness and antioxidant activity (Mattos et al., 2014; Sage and Kubien, 2007; Prasad and Chakravorty, 2015). Furthermore, storaging at 0 °C (below the recommended temperature), some fruits showed lower incidences of chilling injury (e.g. color and texture of the fruits) than the same fruit harvested from the shaded parts of the tree (Mattos et al., 2014).

Management of temperature after the F&V crops are harvested is the most important factor to maintain vitamin C. Its losses are accelerated at higher temperatures and with longer storage durations. Furthermore, under warmer climatic conditions, fruit and vegetable crops will be harvested with higher pulp temperatures, which will demand more energy and refrigerants for proper cooling and may raise product prices (Moretti et al., 2010).

5. Mitigation and adaptation opportunities

Already numerous adaptation strategies that useful under a changing climate are in practices, basically to prolong growing seasons in marginal production areas, improve production and quality in the established production regions (e.g., tunnels and shade netting) (Houston et al., 2018). Several technological and managerial approaches applied across the suppy chain may also help farmers to reduce the anticipated effects (Fig. 4) (Beniston and Fox, 2013; Ravi and Mustaffa, 2013).

Despite agricultural sector is a major contributor to GHG emissions, it also helps to mitigate the impacts of climate change. This is often realized by reducing GHG emissions through enhanced soil carbon sequestration potential and reduction in the emission of nitrous oxide through manure management (Johnson et al., 2007). Johnson et al.

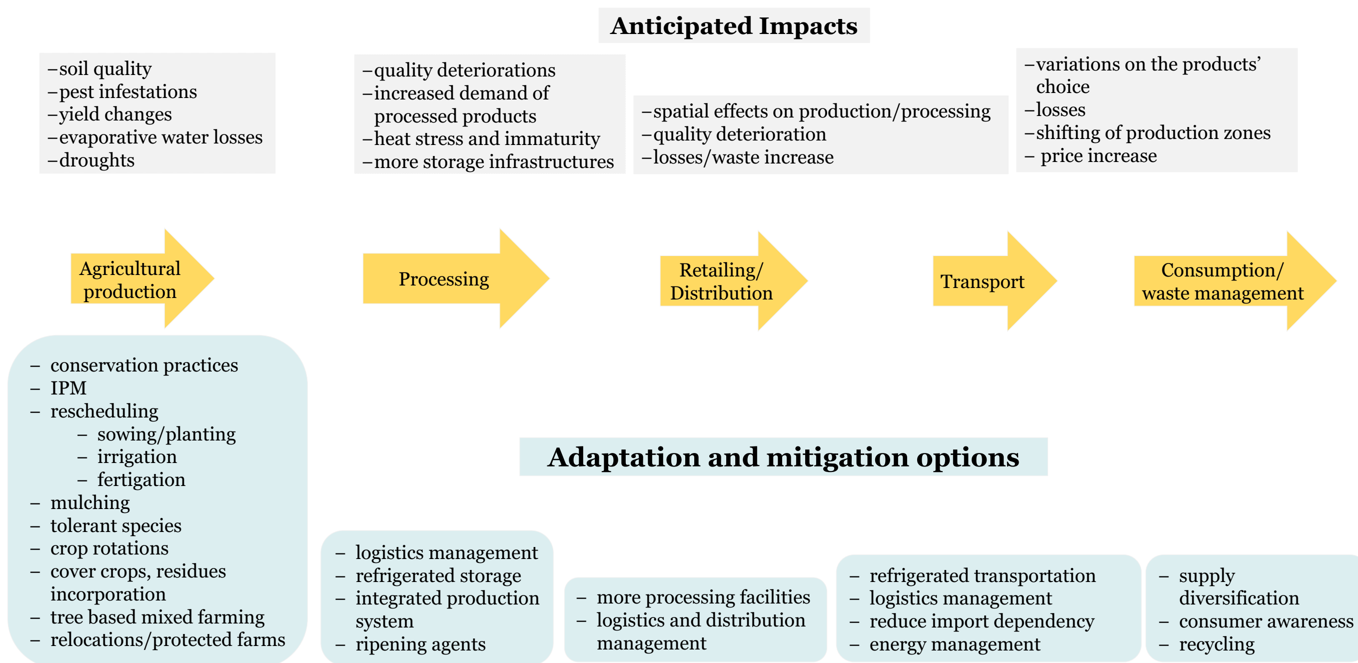

Fig. 4. Effects of climate change and climatic events on F&V products supply chains, along with the potential adaptation and mitigation opportunities (Beniston and Fox, 2013; Ravi and Mustaffa, 2013; Sharma et al., 2013; Sumi et al., 2010).

(2007) further argued that implementation of adaptation measures also enhances mitigation capacity. For example, by adopting different land use management practices (e.g. soil and water conservation, manure and fertilizer management and reduced tillage) the agricultural landscape can help to sequester a substantial amount of carbon in the field and also by reducing methane and nitrous oxide emissions. However, the choice of time-perspective in calculating the GHG emissions due to SOC change is relevant in such cases, but received limited discussion in the selected studies. Martínez-Blanco et al. (2011a, 2011b) argued that soil C sequestration due to compost application during tomato production can mitigate GHG emissions, and assumed the SOC retention at 8% of the C-input (in 100-years perspective). Likewise, in the cases of calculating SOC changes due to agricultural crop residues incorporated to the soil, it is important that the time-perspective is explicitly explained, as the C retention varies (19% to 9.7%) of the net C input in 20 and 100-years, respectively (Parajuli et al., 2017; Petersen et al., 2013). The retentions further vary as per the selection of soil carbon-decay models and the methods (e.g. ROTHC, C-tools and IPCC method) (Coleman and Jenkinson, 1996; Petersen et al., 2013; Watson et al., 2000), where the depth of soil, land use categories, agroecological characteristics of the system investigated can vary the results.

Crop rotation also substantially reduces soil erosion and water runoff, and helps to control insects, disease and weeds (Tilman et al., 2002). Magnitude of climate change impacts, and the responses to the adaptation measures were found spatially varied, and were affected by crop-rotation carryover effects. These included changes in the agronomical characteristics, such as timing of sowing and harvesting, and utilization of residual N in soil. One advantage, as was reported for adapting maize to early-sowing dates under a warmer climate was that due to advance in catch crop establishment residual soil N uptake was enhanced (Teixeira et al., 2018). Other options included, optimized use of resources, e.g., use of bi-products from F&V supply chain, as a source of organic fertilizer or energy recovery through the anaerobic digestion can play important role to save GHG emissions (Bacenetti et al., 2015).

Likewise, to increase the resilient capacity on the water stress, crop varieties with higher tolerance to moisture stress can be considered as substitutes to the current dominant crops. Adaptations to increase resilience in water stressed production regions include enhanced irrigation capacity, improved water monitoring systems and irrigation scheduling, integration of farm drainage systems to manage excess rain into ponds and use during dry periods etc. (Wolfe et al., 2018).

It is also revealed that stakeholders, such as processors, distributors, and retailers can substantially reduce their own impacts. Processing of food commodities, utilization of more durable packaging materials and higher utilization of co-products can significantly reduce food waste. Emphasis on processed products' consumptions are also made since, wastage of processed F&V is about 14% lower than the fresh products (Poore and Nemecek, 2018). Reduction of waste hence can act as one of the mitigation options to numerous environmental impacts.

Meanwhile, considering the wider issue of global food security and the shrinking availability of arable land, the concepts of vertical farming, including urban farming, or multi-floor farming are also evolving, which can be considered one of the adaptation options (Coll and Wajnberg, 2017). Environmental evaluations of such systems are yet very limited.

6. LCA modelling for future production scenarios and research gaps

Drought is one of the crucial challenges among the various vulnerability arising from climate change and seasonal alternations to the agriculture sector. For example, California, a major F&V producing state in the U.S is a drought-prone area and has been regarded vulnerable at meeting the future demand of horticultural crops (Atallah et al., 2014). Alternative sources of water to meet the demand may be available, but at the cost of higher resource requirements and with potential amplification of other environmental problems (Beccali et al., 2009; Stokes and Horvath, 2006). Hence, maintaining the future food supply under changing climatic conditions through proper management of crop water requirement is still among the challenges faced by the region (Atallah et al., 2014; Scanlon et al., 2012; Weare, 2009). Some of the options discussed to address such threats include relocating the production areas to higher rainfall and less drought-prone areas, and/or improving the water magement facilities (Atallah et al., 2014). Assessing environmental and economic costs of relocating the production system is important for evaluating the long-term sustainability. One of the issues in the context of relocating production areas is the

challenge associated with different cultivars. Many horticultural crops harvested from hybrid cultivars developed specifically for the specific production environments (Atallah et al., 2014), example, for broccoli the cultivars are specific to California production conditions (Farnham and Björkman, 2011). Likewise, land use impact, both direct and indirect, is also relevant, particularly if the current production land is left barren or will be utilized for non-food purposes, e.g., as have been considered for bioenergy crops (Efroymson et al., 2016). In these transitions, it is imperative to account the changes in the reference flow of materials (including the land use) so that environmental footprints of a changed system can be quantified and evaluated for screening the best management practices.

Likewise, adaptation and mitigation strategies in the F&V supply chain were argued in the form of implementing (i) conservation practices, to maintain soil quality and water availability, (ii) integrated pest management, (iii) management of cropping practices, e.g. through rescheduling of sowing and planting periods, irrigation, and shifts in the crop calendar, (iv) development of climate-stress-tolerant species, and (v) other potential farm interventions such as integrated tree-based mixed farming to improve biodiversity, introduction of green manuring and cover crops etc. (Fig. 4). An integrated farm e.g. F&V crops with crop rotation can be beneficial to optimize the use of available resources (Bommarco et al., 2013). For instance, Nemecek et al. (2001) presented a case of apple cultivation in Switzerland with a crop rotation. The rotation included crops such as potatoes, winter wheat, grain maize spring barley, grass-clover and forage catch crop. With such integration, it was reported that the area-related-energy use was about 50% lower than the apple production without rotation. Likewise, the pesticide input in the apple farm with a crop rotation was lower by factor of 10 but the aquatic ecotoxicity was not reduced substantially (only higher by a factor of 2 compared to apple grown without rotation). This was mainly due to the heavy metals present in liquid and solid manures that were applied during the production of the non-apple crops (Nemecek et al., 2001), and such feature was similarly reported in Mouron et al. (2006). At this point, it is relevant to state that the choice of LCA method is important, as toxicity related impacts are reported to vary significantly with different methods. As an example, in Dreyer et al. (2003) using the EDIP97 and CML2001 LCA methods, human toxicity potential differed by two-order of magnitude. The reasons behind this were mainly due to: the domination from the metals (in CML2001), whilst in the EDIP97 was due to solvent and nitrogen oxides. However, despite major differences reported for human toxicity, for most of the remaining impact categories, only minor differences are reported. These indicated that numerous farm management options can mitigate the environmental problems, but during the evaluation, a wider environmental impact categories should be considered and knowledge to the LCA frameworks are essential.

Another opportunity is the development of hydroponic systems, primarily to produce food in the regions where water scarcity is very high (de Anda and Shear, 2017). For such areas, compared to the situation of relocation of farms, hydroponic technology may owe environmental benefits, e.g. due to the saving and recycling of resources and also reducing the food miles, which would have increase if there is a shift in the production areas (Specht et al., 2014). Unfortunately, there is research gaps that can illustrate the significance of evaluating these distinct agro-management aspects to maintain the future yield and quality of F&V products.

The basic factors that can support sustainable supply of F&V products are climate, proximity to the producers and the growing seasons. Likewise, logistic management, including facility-locations in the overall supply of F&V products is also connected with the seasonality of production, cost of transportation and the refrigeration/preservation requirements. In the logistic management areas, understanding the relationship between storage and waste is also relevant. Only less than 12% of the reviewed study (Table 1) explicitly considered the wastage at some part of the supply chain. The significance of such considerations can be explained from a Brazilian study, which compared food stores, with and without refrigerated units (Garnett, 2006). The study revealed that waste generation in the un-refrigerated store was 28% higher than the refrigerated store. Furthermore, refrigeration can also assist to improve self-sufficiency of F&V product supplies, and undoubtly it is important aspect while addressing the consequences of climate change on the food security. However, it is important to evaluate the environmental and economic costs of whether storing indigenous products beyond their growing season would outweigh the energy use and other emissions resulting from the transport of imported foods. Atallah et al. (2014) evaluated economic hotspots induced due to localization effects (i.e. effects of transporting the products from one location to another) in the F&V supply systems in the USA. They analyzed the supply chain cost, e.g. relating the changes in the consumer price associated with the product relocation across space and seasons. Furthermore, in many cases, it was suggested that processed F&V products can be stored with lower losses. The significance of promoting processed products may be a mechanism to address the seasonality issues of fresh products and also reduces the transportation costs of fresh products, especially where transportation costs are significant in the overall cost of supplying a product. Reduced loss and transportation costs may result in distribution to meet demand in geographically diverse markets. In the meantime, as discussed in Sections 3.4.5 and 4.2, it is relevant to consider the nutritional values of the different processed products. The transformation of food qualities (nutrient content, such as, carbohydrate, fiber, vitamins, minerals, essential amino acids, energy, fat and protein) are differently-varied according to (i) the types of foods (fresh and processed F&V products) (Nutrient Data Lab, 2007); and (ii) storage and preparation processes (Barrett, 2007; Bouzari et al., 2015a, 2015b; Rickman et al., 2007; Severi et al., 1997). For example, depending on the types of food commodity, freezing and canning processes may preserve the nutrient value, but the initial thermal treatment of a processed product can cause loss of vitamin C and the B vitamins. Likwise, the frozen products lose some nutrients initially due to the short heating time in blanching (e.g. potatoes) and can lose more nutrients during storage (Rickman et al., 2007). If the future adaptation scenarios demand for an increased use of refrigerated transport and the storage, and more processed products, it is then pertinent that the nutrient retention factors of the different products are considered. Here, the significance of defining the rationale functional unit of the F&V products across the supply chain come to be relevant so that products are evaluated on a comparable basis. A nutrient rich indices for different food commodities (Drewnowski, 2009; Saarinen et al., 2017; Tessari et al., 2016) hence can be a useful tool. Such evaluations can help in the decision making process, when future production systems are to be prioritized on the basis of their environmental and economic implications (Huang S.U., 2004) that can accrue due to climate change affecting the food qualties. Unfortunately, environmental impacts of considering these managerial and methodological aspects are very limitedly reported in the currently available LCA literature.

The current limitation of LCA method is that it investigates the production processes that are already established (ex-post, or retrospective). For a prospective LCA, the practitioners have to deal with the technologies in the future, which is the opposite in the “retrospective LCA”as it investigates with the products in the past, regardless of modelling approaches (Arvidsson et al., 2017). The problem may exist to overcome the hurdles of collecting inventory (data) of a system, which is not existing today. As suggested in Arvidsson et al. (2017), the strategies to model the future foreground systems (i.e. the main production system to be assessed) can be in the form of (i) predictive scenarios- evaluating environmental impacts of status quo and most-likely developments, and (ii) considering range of production scenarios- to quantify the life

cycle inventories, and illustrate the potential environmental impact, including in extreme scenarios. Suitable ex-ante LCA approaches can be applied for emerging and future production scenarios (Alfaro et al., 2010; Miller et al., 2012) involving development of the both, the inventory and impact assessments.

7. Way forward

Environmental evaluation of business-as-usual crop production systems and taking care of future prognosis, especially detrimental impacts due to climate change on productivity and quality of F&V crops are relevant. It is important to quantify the damages and thereby to adopt appropriate preventive and adaptive measures. Understanding the potential detrimental effects of climate change on food crops is mostly guided by seeking answers to various sustainability questions, such as how climatic variations may directly and indirectly affect the normal functioning of the ecosystem on which the crop production systems rely. Some of the most alarming consequences are reported to be on the yield and quality of F&V products. Several scientific findings have claimed that impact of temperature-variations is on crop photosynthesis. Increased temperature is anticipated to have an adverse impact on the post-harvest quality of different food products. However, the impacts due to climate change are not uniform across the world, rather they are largely varied according to the geographical locations of the producing regions. A general shift to a milder climate towards the poles could potentially improve crop production, whilst in the tropics, dryer and semi-arid regions, the adverse impact could be a dramatic reduction in agricultural productivity. Higher frequency of extreme and fluctuating weather conditions is also often reported to have unpredictable influences in agroecosystem, e.g. in terms of the crop water requirement and on the interactions among crops, pests and diseases. Eventual short and long-term consequences are related to increased risk of failure of current crop protection strategies. Likewise, to the reduce the potential losses in the processing chain, it is also important to increase the capacity of the processing lines, e.g. storage facilities, refrigerated storage and transportation, and logistics in the supply chain. Another potential option, particularly applicable in more climate vulnerable areas, is the relocation of the production system. Likewise, options to minimize water stress could be the use of improved irrigation facilities that increase water use efficiency. Adaptation and mitigation opportunities against to the induced impact of climate change has also increased interest at assessing the environmental consequences, such as during the land use changes due to changes in agricultural practices, occupations of different crops and farm relocation.

In conclusion, pre-assessment of the anticipated impact of climate change is vital to assess different options to address the adverse impacts. However, it is difficult to make general recommendations because of heterogeneous characteristics of the F&V market and the related environmental impacts. Availability and variability in data that can represent both the complexities of production systems of different regions and the physiological and biological characteristics of different food products are among the challenging tasks for environmental modelling. In this context, prospective environmental LCA can be an accounting tool to measure sustainability metrics across the supply chain, and suggest for the best management practices to address the impacts of climate change in the F&V sector. Inclusion of the following aspects within prospective LCA studies are relevant:

- Impact of changes in productivity: it is relevant to track how changes in the yield of different crops would affect the national/regional/global supply chains; and delineate their sustainability metrics along the supply chains.
- Integrated Pest Management: it is relevant to evaluate future pest management strategies, which may include use of different types of pesticides than that of currently applied, primarily to mitigate the impacts of the developing diseases.
- Water Management: it is impertative to evaluate different water management strategies while adopting solutions to anticipated water stress in different F&V products.
- Soil Quality: assessments of impact of land use changes is relevant, and evaluate the soil organic carbon changes, as a measure of soil fertility and to mitigate GHG emissions. This is also important in a situation if current agriculture production areas are to be relocated/shifted for coping the seasonal and climatic stresses.
- Environmental and economic hotspots analysis: it is relevant to evaluate the environmental and economic burdens of producing and consuming different F&V products, with due considerations of the future variations in the logistics, including storage, refrigeration and transport facilities.
- Impact of different cropping system: evalautions of protected and unprotected farming system, including vertical farms are relevant considering the potential mitigation options, illustrating the measures that can help to reduce impacts related to infrastructure and implements.
- Impact of changes in food preservation and demand: it is relevant to account future life cycle inventories across the supply chain, also taking care of the potential increase in the demand of processed products, without neglecting the nutritional values that the different types of food commodities can provide.

We aimed at carrying out prospective LCA assessments of the future production scenarios incorporating different feasible management options outlined above.

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